A Novel Method for Fabricating Additive Manufactured Lightweight, Optical Quality Metallic Mirrors

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Abstract

Lightweight optics have been a focus for airborne and spaceborne applications in which the size, weight, and power (SWaP) of the system are critical. Many different methods for fabricating low-weight optics are in use today. We present a novel methodology for generating lightweight metallic mirrors fabricated by growing an additive manufactured blank, post processing the faces, coating with electroless nickel, and diamond turning. Test coupons were characterized and compared against performance specifications. The process was then used in a case study of the development of a low-weight spinning mirror, in which topology optimization was used. The blank was then fabricated with metallic powder bed fusion and post processed to deliver optical quality mirror surfaces. Through this case study the flexibility of this novel post processing method is demonstrated; enabling complex metal additive manufactured blanks to be processed into high quality mirrors greatly expanding the design space. This technology has the opportunity to reduce cost and increase the performance in many optical applications.

Introduction

In engineering system design, there has always been the drive to reduce the SWaP of a system. This is of paramount importance in the development of aircraft and spacecraft, where every additional pound of payload increases the cost of operation over the 30-year life of the

aircraft by $40,000, or a spacecraft launch by $10,000 [1,2]. The use of aircraft and spacecraft for surveillance creates a demand for lightweight optics. The benefit of lightweight optics is compounded when the optic is actively actuated in the system, and therefore, the mass of the optical component drives its own loading, called self-weighting. As a result, lighter mirrors can lead to great reductions of mass in full systems [3,4].

The state of the art in this industry is ULE™, Zerodur™, or beryllium isogrid mirrors. The isogrid design is a standard in which a solid block of material is polished on one side to a mirror surface while the other side is machined with pockets to remove substantial mass yet maintain much of the stiffness [3]. In 2018, when the James Webb Telescope is launched, its main mirror comprises 18 beryllium hexagonal sub components at a target cost of $150M and will have required eight years to complete [5,6].

While the performance of beryllium isogrid mirrors is exceptional, the manufacturing cost and lead times are serious limitations. The cost is very high because of both the rarity of beryllium and the high toxicity of particles during fabrication. Many systems instead utilize metal reflective optics made of aluminum due to their ease of processing and cost, as well as system-level design constraints on material ubiquity or mass. There has been a great deal of work to explore methods to generate lightweight non-beryllium mirrors beyond the typical isogrid design. One of those methods explores the bonding or brazing of aluminum face sheets to aluminum foams to create sandwich panels [7]. This technique creates many challenges of its own due to the bonding, assembly, and risk of delamination. Composite replica molded mirrors are also being investigated, but they require expensive tooling and pose risks from a material longevity standpoint [4].

Additive Manufacturing of End-Use Parts

While additive manufacturing (AM) has existed for 30 years, only in the last decade has Rapid Manufacturing (RM) become widespread. RM is the practice of creating end-use parts by AM, meaning that they will be fully utilized not as prototypes, but as final parts [8]. This transition has been spurred both by the development of better machines and materials and also by more informed designers and more inventive applications.

The ability to generate additive metallic end-use parts opens the opportunity to create mirrors with far greater geometric complexity than previously constructed. Monolithic parts can be made with variable density, in which both sparse low-mass regions and solid regions exist. Thus mirrors can be grown with low-mass areas for stiffness and connectivity and solid face sheets for the mirror surfaces, allowing lighter, higher performance mirrors to be created.

Paper Structure

This paper addresses two separate questions. The first was whether additive-manufactured mirror blanks could be post processed to enable high-quality mirror surfaces, comparable to those made conventionally. This question was critical because it would demonstrate the applicability of the proposed finishing method since there were challenges to overcome the non-standard alloys and levels of porosity bulk metallic properties of the printed material. The second question was how additive-manufacturing design freedoms could be leveraged to deliver a higher performance mirror. Because the latter question was conditional on the success of the first (to create high-quality mirror surfaces) these two topics will be covered sequentially. We expected that if the viability of the process could be demonstrated the design freedom of AM could be applied to the design of novel mirror geometries disrupting typical manufacturing to enable an expansive design space.

Proposed Method

Substrate Fabrication

Given the desire to create highly intricate metallic geometry, Powder Bed Fusion (PBF) was selected for fabrication. PBF is a process where layer-by-layer parts are created by fusing small particles of material together through the selective application of thermal energy. For metallic powder bed fusion, high residual stresses are generated during part fabrication, frequently requiring support structures during fabrication and stress relief before being removed from their build plates. It was decided to test two different technologies within PBF: Electron Beam Melting, where an electron beam is used to create the thermal energy for fusion, and selective laser melting, where a laser beam is used to generate the thermal energy.

For Electron Beam Melting, an Arcam Q10 machine was used. For Selective Laser Melting, an Electro Optical Systems (EOS) M280 machine was used.

Two different materials— titanium and aluminum (specifically Ti6Al4V and AlSi10Mg) — were evaluated for this project. They were selected for their high specific strength, low density, and prevalence in AM. It is important to note that the current generation of Arcam machines is unable to process aluminum; therefore, aluminum was only tested using on the EOS laser based system.

Two phenomenological effects of the PBF process need to be overcome by the finishing technique. First, porosity exists in bulk metallic PBF, where the density is typically 99.5% but not unity [9]. Any voids had the potential to create imperfections in mirror surfaces. Second, as the surfaces of a PBF part are created, a layer of partially fused powder adheres to the surface, thus creating a low-density region that must be removed to obtain material of bulk properties [10].

Mirror Finishing Techniques

Metal reflective optical substrates are commonly post-processed to achieve optical characteristics such as flatness, angularity, roughness, and reflectance. The diamond turning process removes small amounts of material to achieve flatness on the order of one micron and surface roughness on the order of one nanometer [11]. Materials with high ferrous content are not readily diamond turned due to enhanced tool wear caused by galling and micro-welding. Similarly, materials with a particularly hard or brittle oxide layer lead to tool damage and wear. The tool dimensional instability and dulling reduce the capabilities of the diamond turning operation. This limits the use of many prevalent metal additive materials, including high silicon content aluminum, titanium alloys, and alloys with high molybdenum content, such as 316 stainless steel.

A thin coating may be applied to a substrate to increase machinability. A coating more tuned to the diamond turning process can be used to preserve tool integrity, reducing dimension instability caused by premature wear and dulling. One such coating is electroless

nickel. This coating is readily machinable by diamond turning. It has added optical advantages such as temperature stability, high reflectivity, and resistance to corrosion.

In this project, the substrates produced by AM were post processed to achieve the desired optical characteristics. For this proposed process, initial surface material removal was performed by fly cutting the optical surface with a standard machine tool. The additively manufactured substrate was oversized by up to 0.030 in to compensate for this material removal. This created a more tightly constrained optical geometry, flat to 0.001 in and parallel to 0.002 in, as well as removed the porous surface layer of the part. The optical surface was machined to a surface figure 0.001-0.005 in smaller than nominal. The part was then heated to 320°F for 18 hours to relieve residual stress from the sintering and machining processes to prevent subsequent material deformation.

After the first machining step, electroless nickel was deposited on to the substrate in a 0.005 in layer to provide a basis for diamond turning and coating. This critical step made additional processing of the substrate nearly material independent. Substrate and nickel materials must still be matched to prevent delamination or bimetallic stresses in extreme environments. The part was then put through a standard diamond turning operation. The diamond-turning tool removed a layer of nickel to create optically suitable surfaces. The final step was material coating. Standard coating processes could be used with this process for the desired optical performance, including antireflective coatings and diamond-like carbon coatings. For our samples, an AlMgF coating was used to increase reflectance of the mirrors and enhance surface toughness.

Test Samples

To prove the viability of the finishing process, 1 in by 1 in by ¼ in square test samples were made and analyzed. Two common AM powder bed metallic processes were used: EBM and SLM with two common lightweight materials, Ti-64V and AlSi10Mg. Additionally, two separate finishing processes were investigated, shown below in Figure 1.

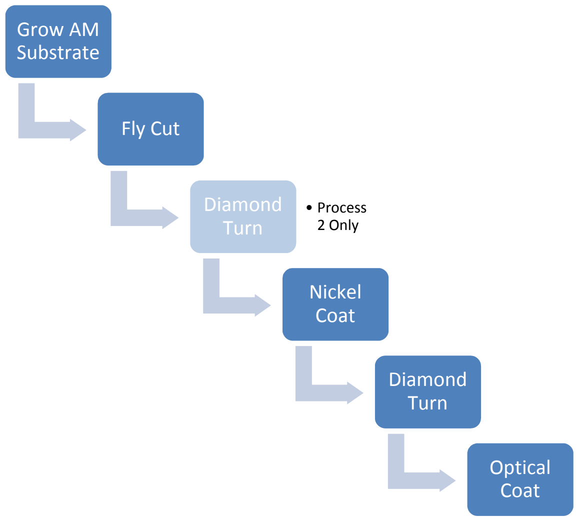

Figure 1: Optical Process Flow Chart, Process 2 shown, process one excludes first diamond turning operation.

For both processes one and two, samples were produced with PBF. They were then machined to mirror surfaces. The differentiating step was included for process two in which the sample was diamond turned prior to coating. This additional step was added for aluminum samples to aid in the holding the required tolerances of the parts. The samples were next coated with a layer of electroless Nickel. The Nickel layer was diamond turned, and the sample was given a final optical coating.

Results

Each test sample was inspected using an optical profilometer capable of calculating surface roughness (both peak to valley and RMS) over a two dimensional plane in units of waves at 633 nm. Sample profilometer output is shown in Figure 2. Full results are listed in Table 1.

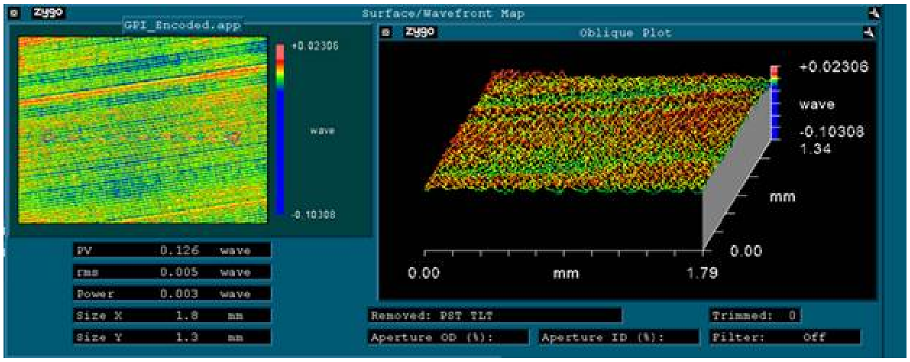

Figure 2: Sample Profilometer Output

Peak-to-valley (PV) and root mean square (RMS) measurements were taken to characterize the rugosity of the surface. Optical power was also measured to give an indication of bulk surface figure away from a nominal flat profile. These results are consistent with the surface figures necessary for many optical systems that can currently utilize metal reflective optics. A similar imagining system, for example, would be diffraction limited (ideal image quality) with roughness specifications on the order of 0.2 wave (633nm) PV and 0.013 wave (633nm) RMS, and power specifications on the order of 1 wave (633nm) [12].

Table 1: Optical Properties of Test Samples

– * values that do not meet specifications

Sample Number	**Material**	**AM Process**	**Optical Process**	**PV (wave)** Typ (0.200)	**RMS (wave)** Typ (0.013)	**Power (wave)** Typ (1.000)
1				0.126	0.005	0.003

2 3	AlSi10Mg	DMLS	1	0.059 0.080	0.006 0.006	0.004 0.004
4 5 6	AlSi10Mg	DMLS	2	0.085 0.549* 0.099	0.013 0.015* 0.017*	0.000 0.007 0.011
7 8 9	Ti6Al4V	EBM	1	0.355* 0.103 0.808*	0.005 0.006 0.014	0.002 0.001 0.007
10 11 12	Ti6Al4V	DMLS	1	0.120 0.180 0.582*	0.011 0.010 0.012	0.014 0.000 0.002

The surface figures would be inadequate for systems with shorter wavelengths or that utilize optical designs dependent on low surface error for aberration control. Metal optics are not an option for these systems currently due to limitations of the diamond turning process in wrought as well as additive materials [12].

These results are particularly promising for mid-and long-wave (3000nm-15000nm) infrared imaging applications, in which diffraction limited optical performance is possible with sub-micron surface error. The parallel peaks and valleys evident in Figure 2 are prevalent in all diamond turn test samples and are characteristic of the diamond turning process. This banding is unrelated to the build orientation of the substrate.

This sample data shows that finished characteristics are of limited dependence on process and material. Both DMLS and EBM are suitable for finishing, as well as both materials tested, AlSi10Mg and Ti6Al4V. This opens the flexibility to design based upon structural and performance constraints.

Spinning Mirror Case Study

The second phase of the project centered on applying the AM mirror surfacing technique to a real-world problem. The problem chosen for this was a high-speed spinning mirror for an imaging application. The system performance drives a requirement for low face deformations under inertial loading from high-speed rotation. This problem was particularly well suited to this methodology because the primary loading of the mirror is self-weighted loading driven by the mass of the mirror itself. Therefore, as mass is cut from the design, the loading is also reduced, providing positive feedback that helps dramatically reduce weight.

The mirror is required to spin at a constant rate of 21 Hz about its center axis. The geometry is constrained by the requirement for optical surfaces as well as mechanical interface with the motor. For system packaging efficiency, the motor is installed inside of the mirror body, and interfaces with the optic on one side, as shown in Figure 3. Optical surfaces must deflect no more than 500 nm RMS across a face under rotational loading.

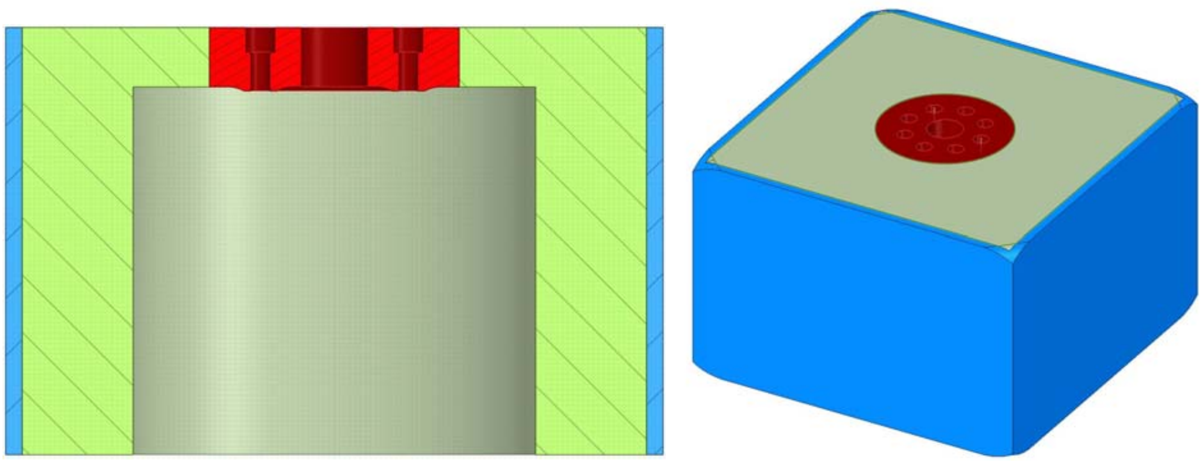

Figure 3: Mirror bounding volume: Red portions defined mechanical interface regions that cannot be modified. Blue portions are mirror faces and cannot be altered. The central void houses the drive motor and is unavailable. Green is the design volume.

Design for AM Mirrors

Driven by the functional requirements for the mirror, topology optimization was selected as a CAD tool to create the design. Topology optimization is a method for generating optimal material distribution given a certain set of constraints, load conditions and an objective[13]. Often resulting in complex structures, there is a powerful synergy between the

shapes generated through this process and the freedom of additive manufacturing [14–16]. Traditionally, engineers have been taught to consider carefully design for manufacturing, design for assembly, and past designs for inspiration. To effectively design for AM, much of this must be put aside given the dramatically different process requirements.

Topology optimization for this project served not only for inspiration as it is often currently used, but also as a way to generate finalized geometry. To avoid the reinterpretation of the topology optimized output model from a mesh back into a solid model (a process that fights complexity), the decision was to instead edit the mesh directly. This provided two distinct advantages. First it saved the enormous effort of translating a complex design into a parametric model. Second, it embraced the link between the triangular mesh used in STL description of 3D models with the tetrahedral mesh used for the analysis and optimization, enabling quicker transition between design and analysis.

Results:

Utilizing these methods, we created much lower mass mirrors with functional properties equivalent to that of the traditional ones that had been used. In Figure 4, the two different designs are shown side by side for comparison.

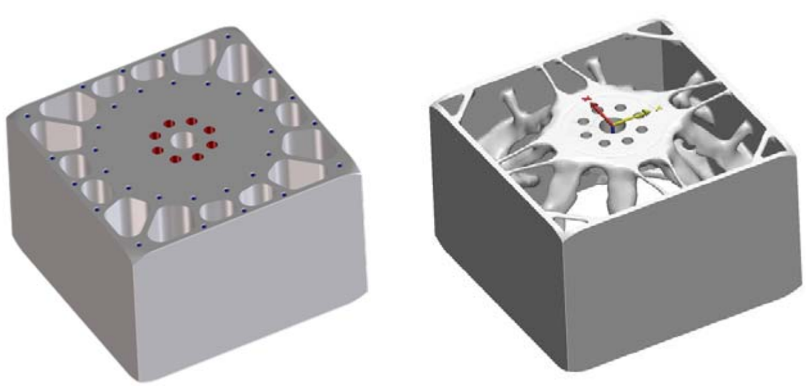

Figure 4: Traditional mirror design on left, additive mirror design on right

The AM design for the mirror was 62% lighter than the conventional design with a surface deflection of 420 nm, remaining under the required 500 nm threshold for surface deflection. Both mirrors were manufactured for similar costs and in a similar amount of time. For both

mirrors the most resource intensive element was the diamond turning and surface coatings that tend to be the most expense and time consuming part of mirror fabrication.

Conclusion:

Our results indicate that this methodology provides an effective means to fabricate complex, lightweight mirrors. Initial testing showed that a variety of different processes, finishing techniques and materials produced high-quality mirror surfaces on AM substrates. We believe that this is a very promising approach to the fabrication of lightweight mirrors for weight critical applications, particularly for designs in which self-loading is substantial or the mirror must be positioned rapidly. For either of the cases, having a lower weight mirror enables substantial system-level weight reduction. Additionally, we are interested in the use of this technology to enable cost-effective fabrication and development of free form optics.

We are interested in conducting further research into this area, yet it is important to explore larger sample sizes as this study only examined small numbers of artifacts. Finally, we believe it would be valuable to conduct durability testing on these mirrors to ensure that the electroplated coatings remain effective over significant time periods.

Research and development are currently underway to enable printing of Beryllium through the EBM process [17,18]. It is expected that a similar process to the one described in this paper could be applied to a Beryllium mirror using either electroless nickel or gold plating to build up a surface for the mirror finish. While the printing of this toxic material is a challenging task, the use of Beryllium powder to create net shape vacuum pressed blocks is common [19]. This gives some promising indications for AM of Beryllium. Doing so would enable the geometric benefits of AM with the high specific strength of Beryllium to produce very efficient mirrors.

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